Cold excitons

Introduction
- Excitons and electron-hole plasma in semiconductors
- Exciton condensation
- Experimental systems
- Indirect excitons in coupled quantum wells

Phenomena in cold exciton gases
- Stimulated scattering
- Pattern formation and transport
- Coherence and condensation

Control of excitons, excitons in potential landscapes
- Optical traps
- Excitonic circuits
- Excitons in traps
- Excitons in lattices

Spin transport of excitons

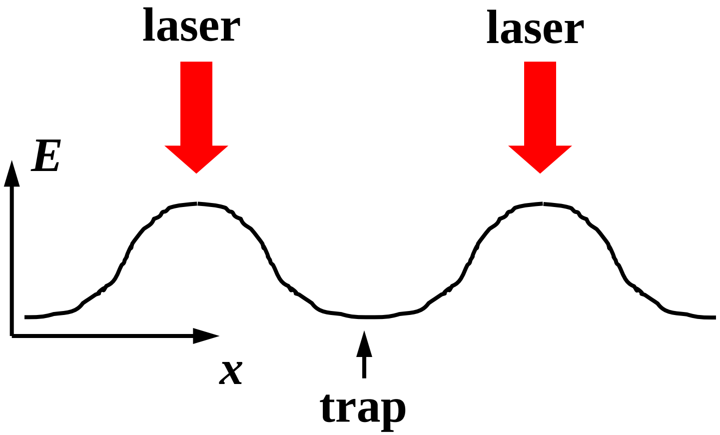
Most recent studies
- Topological defects in interference pattern
- Spin pattern formation

optical traps

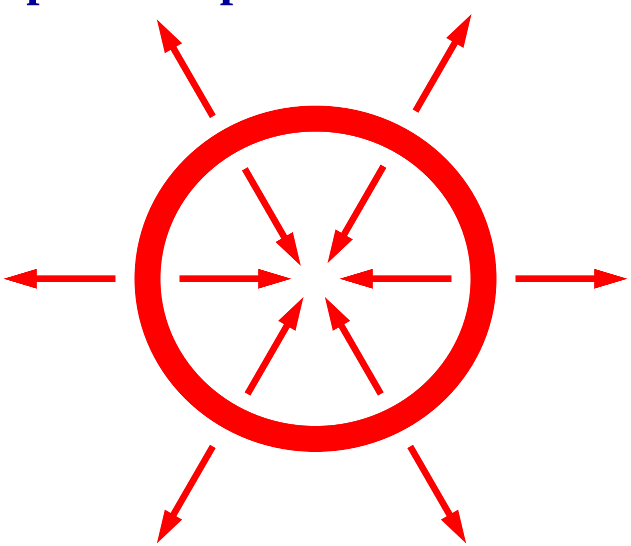
in biology:
manipulation of DNA, viruses & cells by optical tweezers

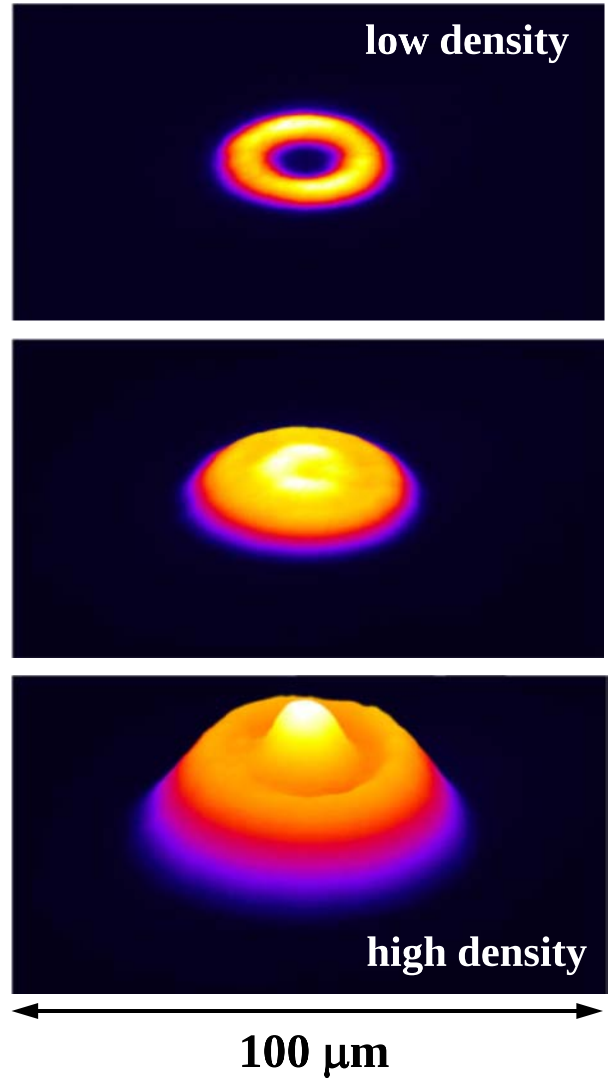
in atomic physics:
development of methods to cool and trap atoms with laser light
→ atom BEC in optical traps

Trapping of cold excitons with laser light

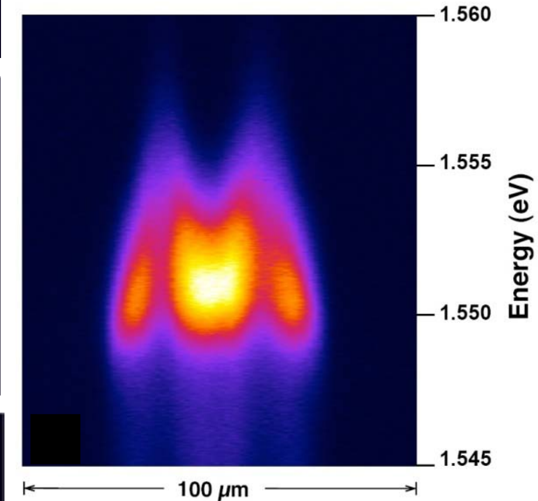


- can be switched on and off
- no heating in the trap center
  → excitons are cold in the trap
- ability to form various potential patterns



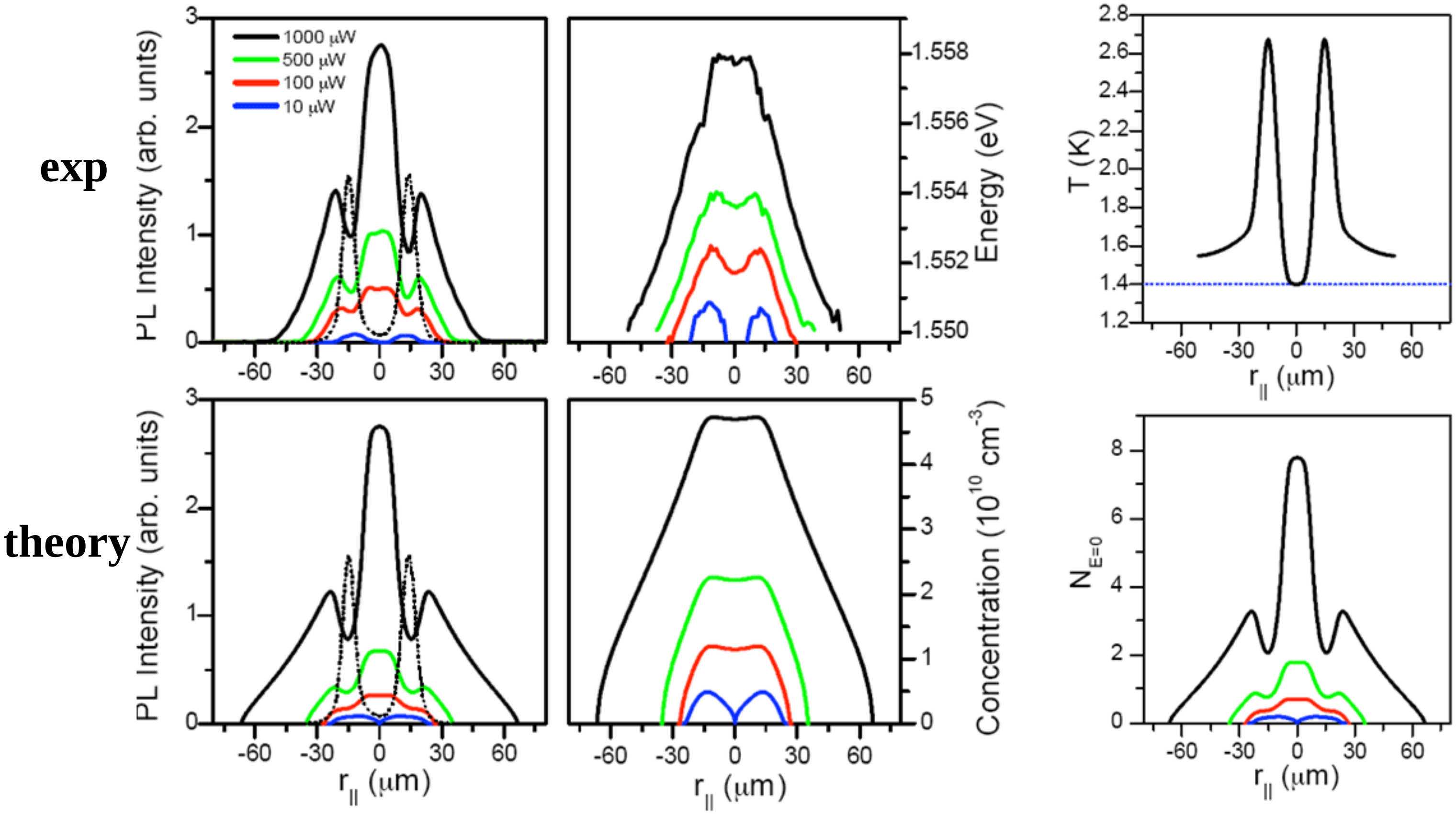


experimental implementation



A. Hammack, M. Griswold, L.V. Butov, A.L. Ivanov, L. Smallwood, A.C. Gossard, PRL 96, 227402 (2006)

Experimental data for exciton PL, density, and energy distribution in laser-induced traps vs theory



excitons are cold in the trap center with $T_X = T_{lattice}$

the trapping of a highly degenerate Bose gas of excitons in laser induced traps

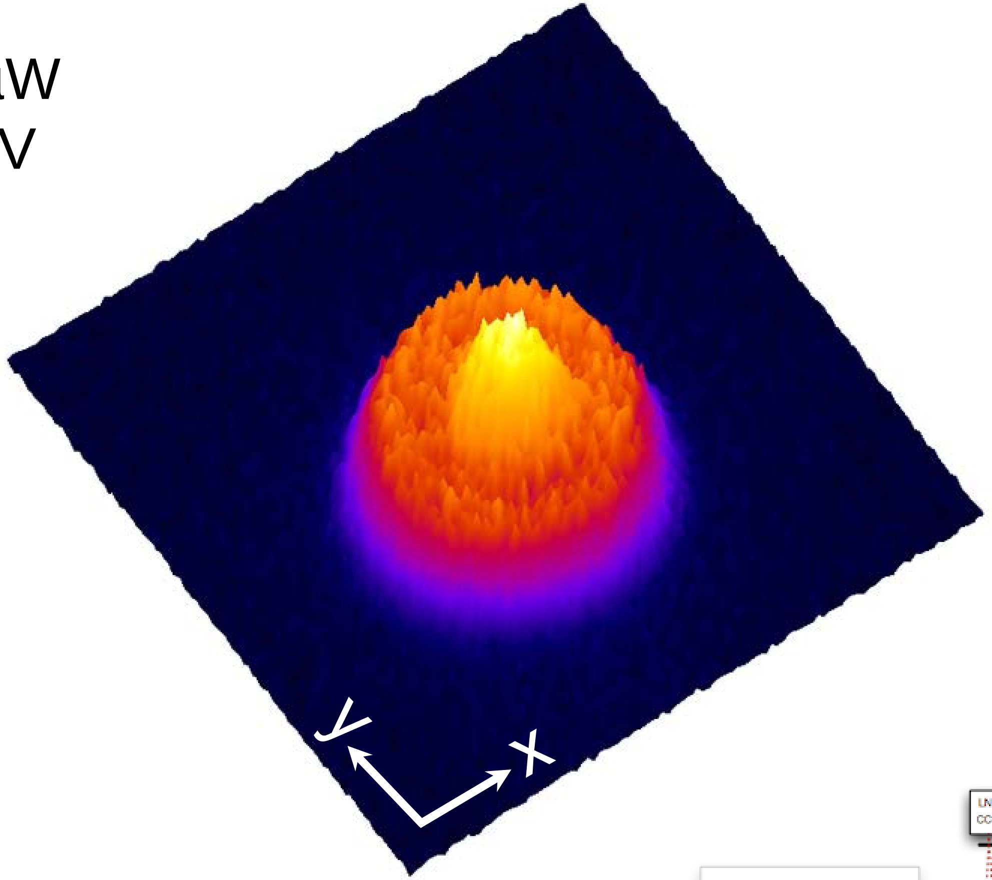
$$U_{trap}(x,y) = \delta E(x,y) = \frac{4\pi e^2 d}{\varepsilon} n(x,y)$$

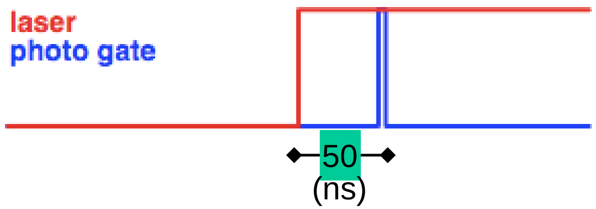
$$\left.\begin{array}{r} \delta E \approx 8 \text{ meV} \;\Rightarrow\; n \approx 5\times 10^{10} \text{ cm}^{-2} \\ T \approx T_{bath} = 1.4 \text{ K} \end{array}\right\} \longrightarrow N_{E=0} = e^{T_{dB}/T_X} - 1 \approx 8$$

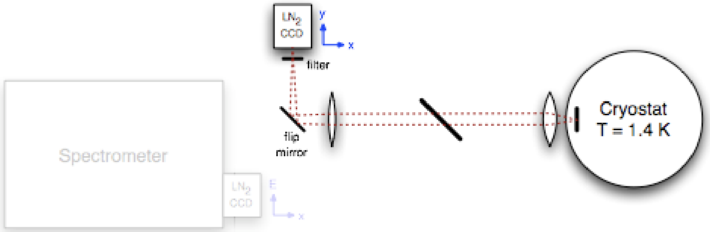
A. Hammack, M. Griswold, L.V. Butov, A.L. Ivanov, L. Smallwood, A.C. Gossard, PRL 96, 227402 (2006)

Exciton collection to laser-induced trap

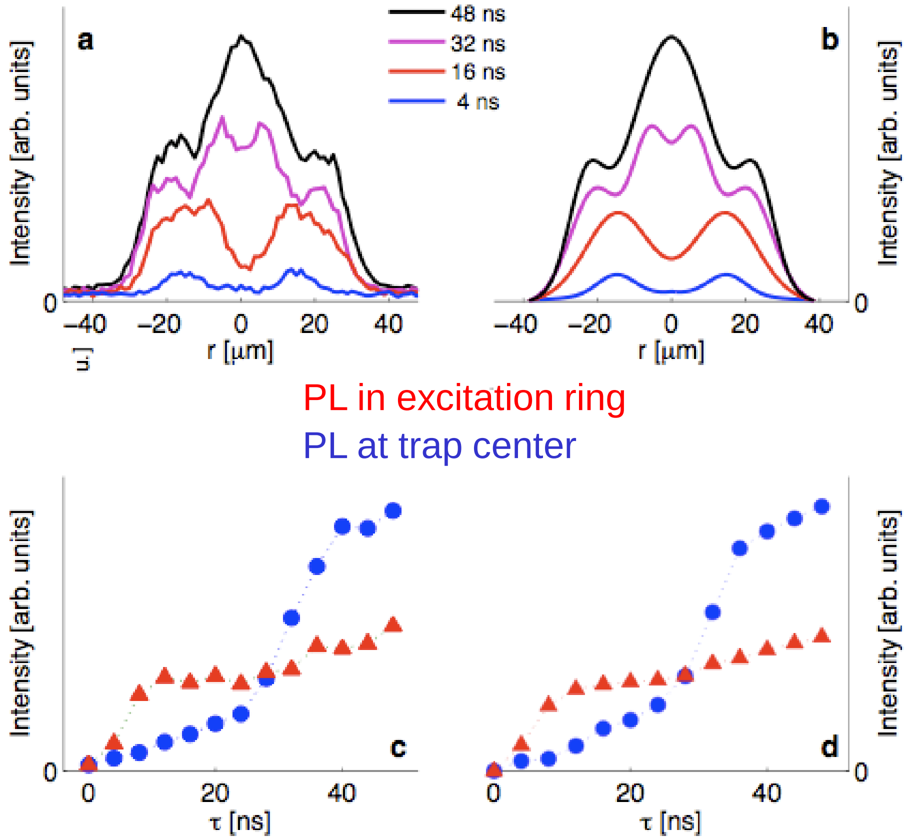
P_{ex} = 75 μW
V_g = -1.2 V
δ = 4 ns







experiment **theory**



observed hierarchy of times

(*exciton cooling time*) < (*trap loading time*) < (*exciton lifetime in the trap*)

$T_{cooling\ to\ 1.5\ K} < 4$ ns $\tau_{loading} \sim 40$ ns $\tau_{lifetime} \sim 50$ ns – 10 μs

is favorable for creating a dense and cold exciton gas in the traps and its control *in situ*

A. Hammack, L.V. Butov, L. Mouchliadis, A.L. Ivanov, A.C. Gossard, PRB 76, 193308 (2007)

Excitonic circuits

Excitonic circuits

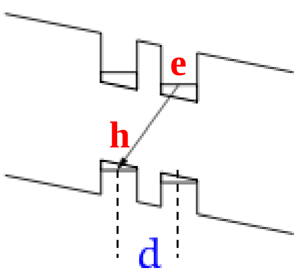
the ability to control <u>electron</u> fluxes by an applied gate voltage

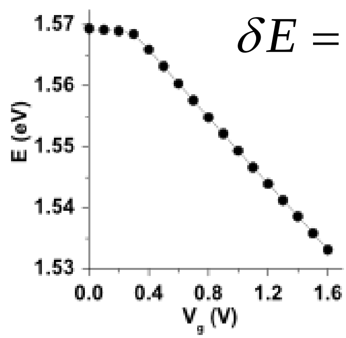
electronic circuit devices

mesoscopics

the field which concerns electron transport in a potential landscapes

potential energy of indirect excitons can be controlled by voltage





$$\delta E = edF_z$$

in-plane potential landscapes
can be created for excitons by voltage pattern
e.g. circuit devices, traps, lattices

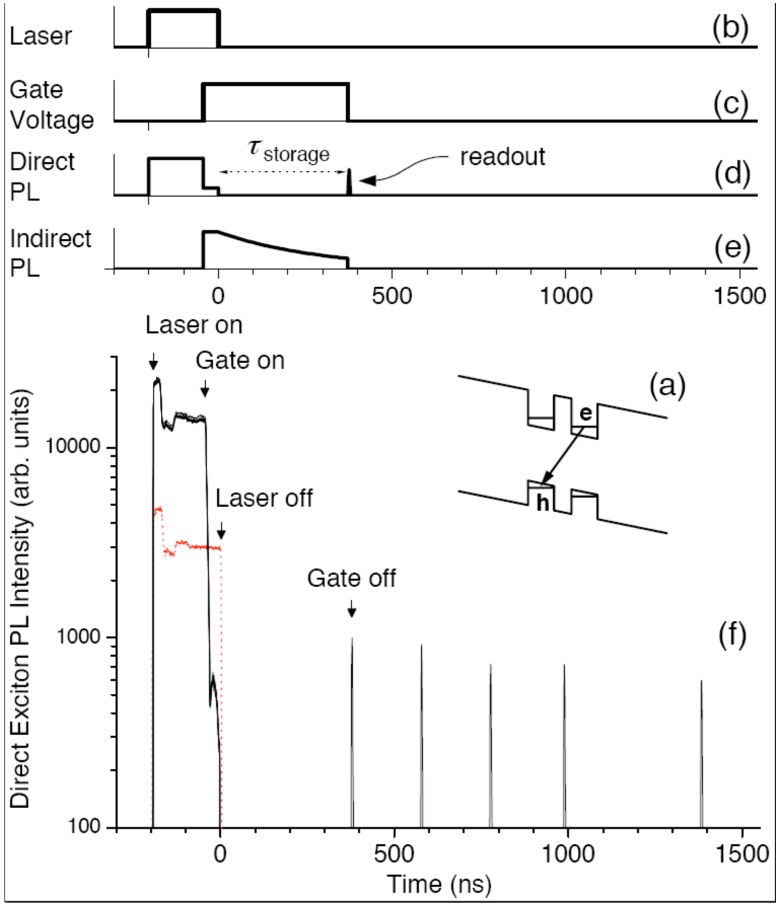
the ability to control <u>exciton</u> fluxes by an applied gate voltage

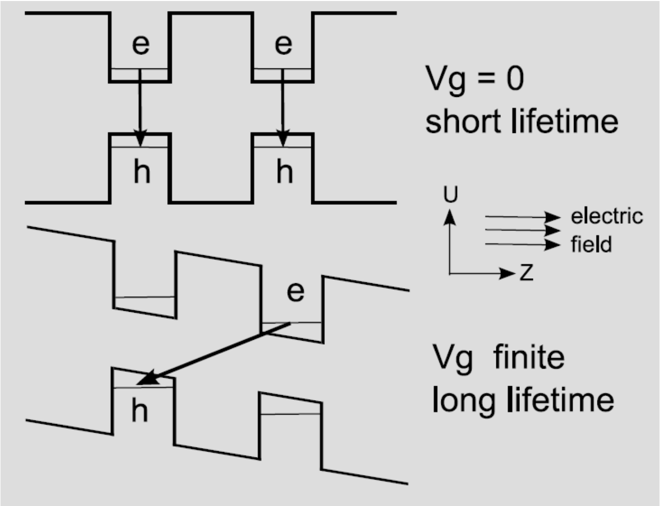
excitonic circuit devices

delay between signal processing and optical communication is effectively eliminated in excitonic devices → advantage in applications where interconnection speed is important

mesoscopics of bosons in semiconductors

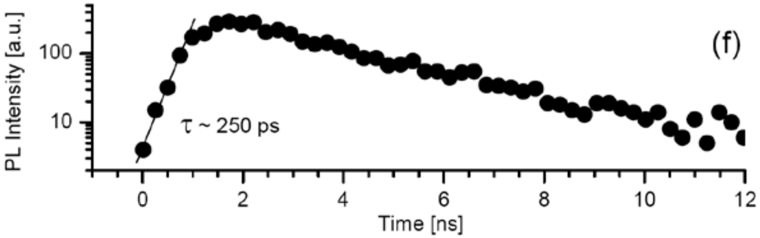
Storage





store photons in the form of indirect excitons

storage and release of photons is controlled by gate voltage pulses



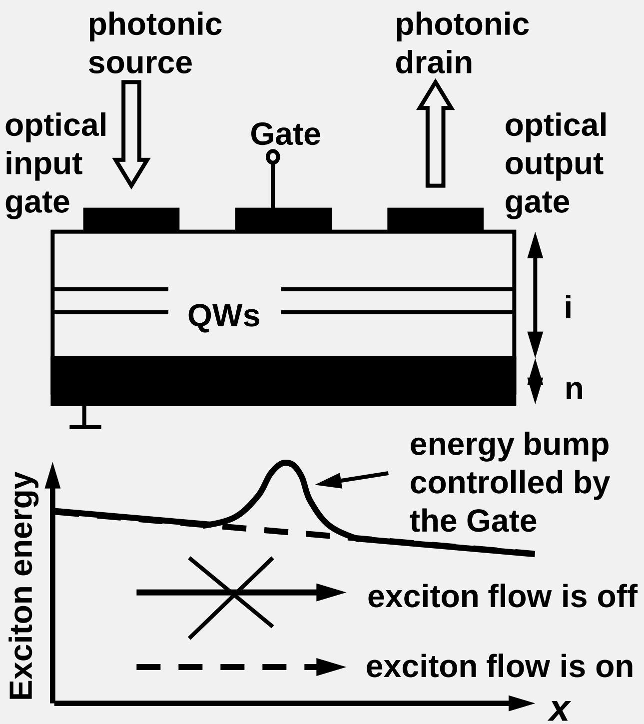
prototype of storage device reaches sub-ns switching time and several μs storage time

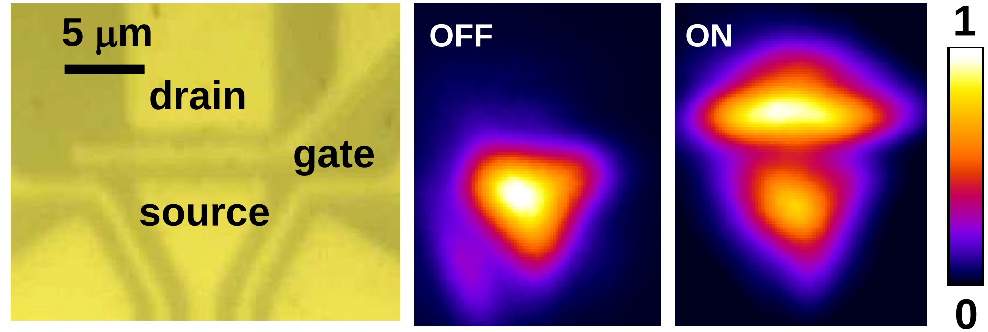
A.G. Winbow, A.T. Hammack, L.V. Butov, A.C. Gossard, Nano Lett. 7, 1349 (2007)

A.G. Winbow, L.V. Butov, A.C. Gossard, JAP 104, 063515 (2008)

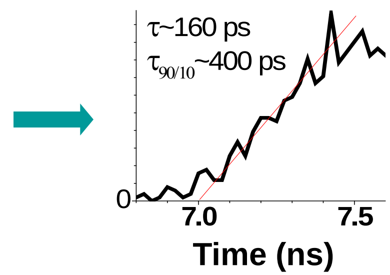
Excitonic Transistor

operation principle of excitonic transistor similar to electronic FET with excitons in place of electrons





switching from OFF to ON



- *Fast*: switching time combined with the interconnection time for the first proof-of-principle excitonic transistor was ~ 0.2 ns
- *Compact*: In the first proof-of-principle excitonic transistor the distance between the source and drain was 3 μm
- *Scalable*: have architecture and operation principle similar to electronic FET

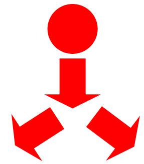
Major challenges: Finite exciton lifetime
Finite exciton binding energy

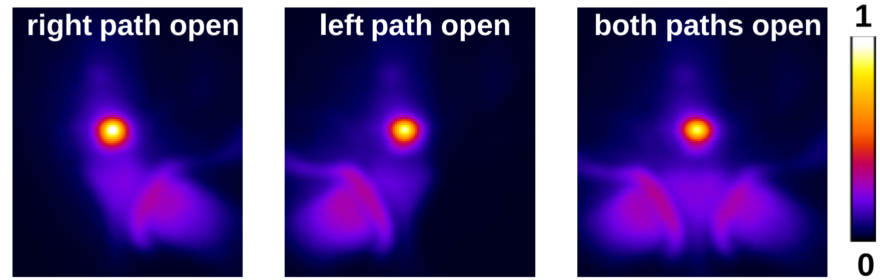
A.A. High, A.T. Hammack, L.V. Butov, M. Hanson, A.C. Gossard, Opt. Lett. 32, 2466 (2007)
A.A. High, E.E. Novitskaya, L.V. Butov, M. Hanson, A.C. Gossard, Science 321, 229 (2008)

Excitonic IC (EXIC) with 3 Excitonic Transistors

Prototype EXIC performs directional switching

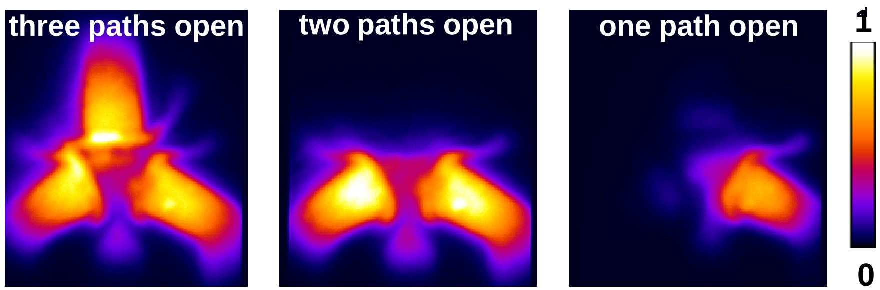
Flux of excitons photoexcited at ● is directed by gate control





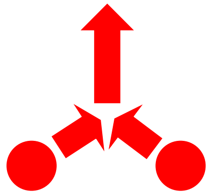
Prototype EXIC performs directional switching

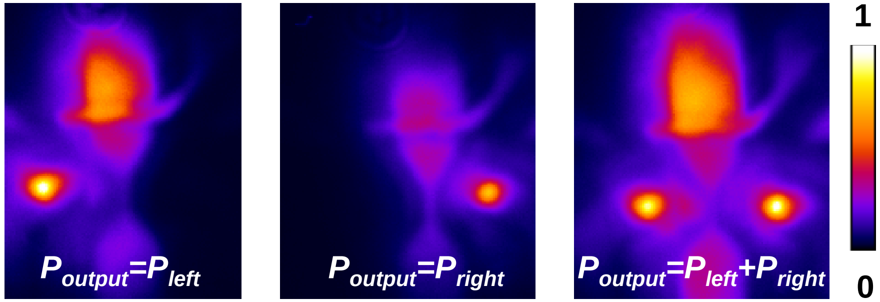
Flux of excitons photoexcited at ● is directed by gate control



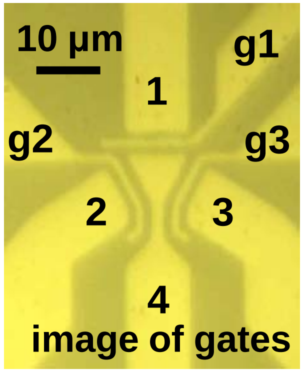
Prototype EXIC performs flux merging

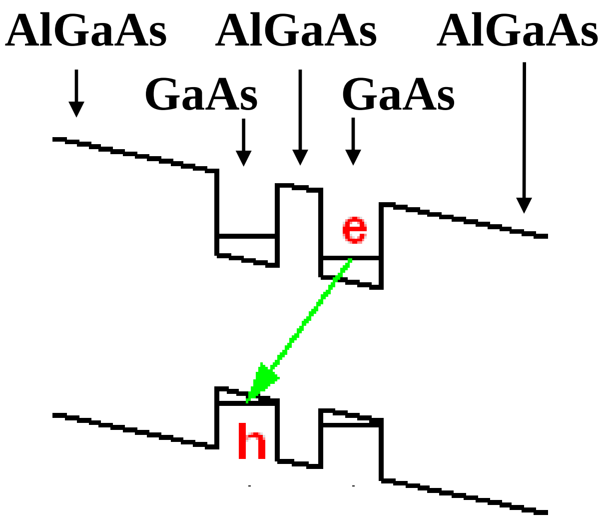
Two fluxes of excitons photoexcited at ● are combined by gate control. The device can implement sum operation and logic gates.





A.A. High, E.E. Novitskaya, L.V. Butov, M. Hanson, A.C. Gossard, Science 321, 229 (2008)



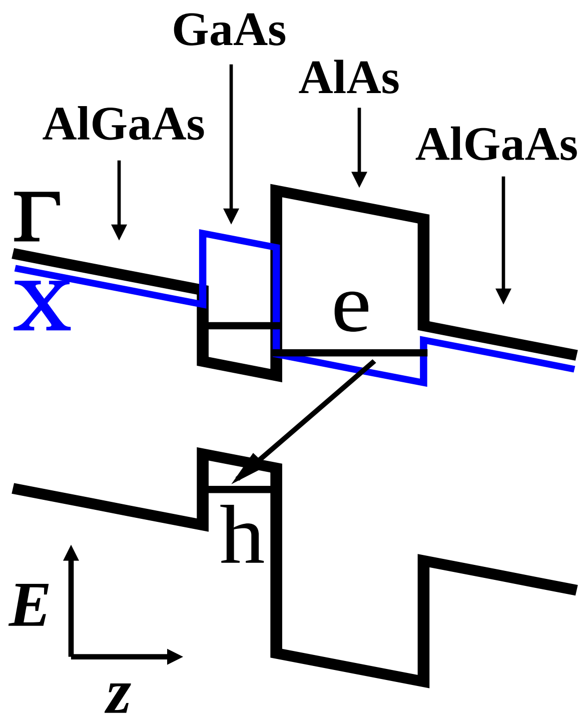


GaAs/AlGaAs CQW
$d \approx 12$ nm
$E_{ex}/k_B \sim 40$K

operation at T = 1.5 K:

A.A. High, A.T. Hammack, L.V. Butov, M. Hanson, A.C. Gossard, Opt. Lett. 32, 2466 (2007)

A.A. High, E.E. Novitskaya, L.V. Butov, M. Hanson, A.C. Gossard, Science 321, 229 (2008)



AlAs/GaAs CQW
$d \approx 3$nm
$E_{ex}/k_B \sim 100$K
makes possible the operation of excitonic devices above the temperature of liquid Nitrogen

operation up to ~ 100 K:

G. Grosso, J. Graves, A.T. Hammack, A.A. High, L.V. Butov, M. Hanson, A.C. Gossard, Nature Photonics 3, 577 (2009)

Excitons in traps

Early works on electrostatic trapping of indirect excitons

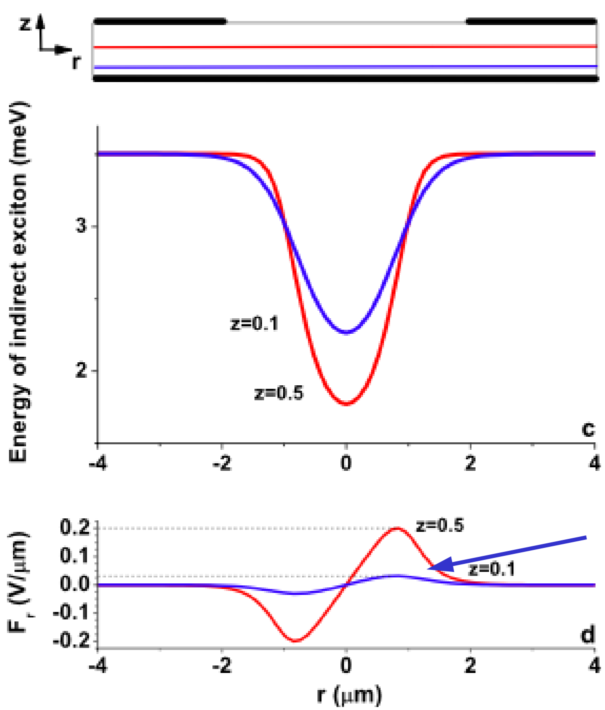
S. Zimmermann, A. Govorov, W. Hansen, J. Kotthaus, M. Bichler, W. Wegscheider, PRB 56, 13414 (1997)
T. Huber, A. Zrenner, W. Wegscheider, M Bichler. Phys. Stat. Sol. (a) 166, R5 (1998)

Obstacle in early works → in-plane electric field dissociated excitons

Solution: to position CQW layers closer to the homogeneous bottom electrode

1999 – calculations, 2005 – experiment

A.T. Hammack, N.A. Gippius, Sen Yang, G.O. Andreev, L.V. Butov, M. Hanson, A.C. Gossard, cond-mat/0504045; JAP 99, 066104 (2006)



CQW far from top gate reduces in plane field F_r

no exciton dissociation

$$eF_r a_{ex} << E_{ex}$$

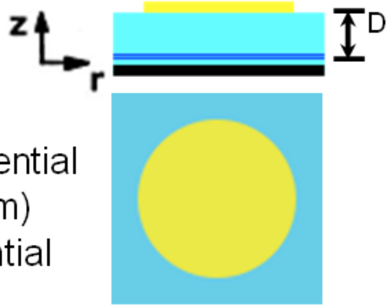
dissociation rate vs F_r

$$\frac{\Gamma_{2D}}{R_y} = \frac{64}{\sqrt{\pi}} \left[\frac{R_y}{eF_{||}a_0}\right]^{1/2} \exp\left[-\frac{32R_y}{3eF_{||}a_0}\right]$$

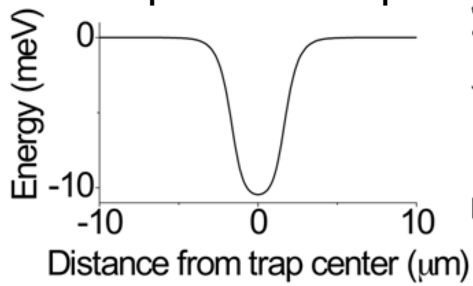
D.A.B. Miller, D.S. Chemla, T.C. Damen, A.C. Gossard, W. Wiegmann, T.H. Wood, C.A. Burrus, PRB 32, 1043 (1985)

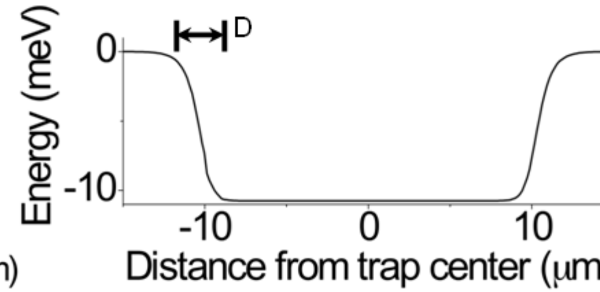
Diamond-shaped traps

Circle Trap



- single electrode
- parabolic-like potential for small radii (<3µm)
- box-shaped potential for large radii

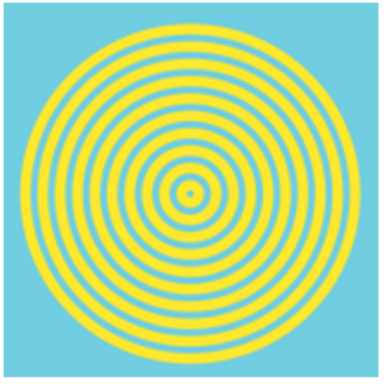


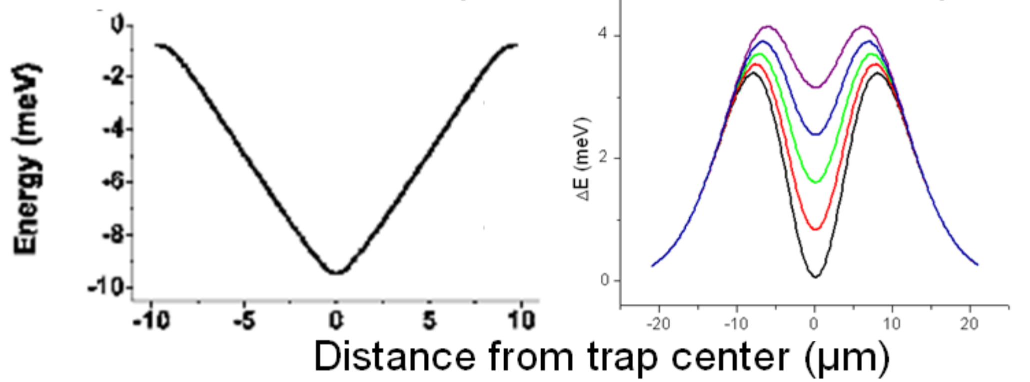


Concentric Rings Trap

- multiple electrodes
- versatile potential profiles

A.T. Hammack, N.A. Gippius, Sen Yang, G.O. Andreev, L.V. Butov, M. Hanson, A.C. Gossard, JAP 99, 066104 (2006)



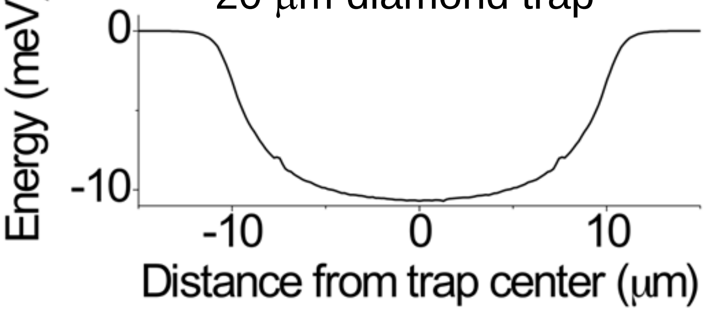


Diamond Trap

- single electrode
- parabolic-like trap even for large lengths

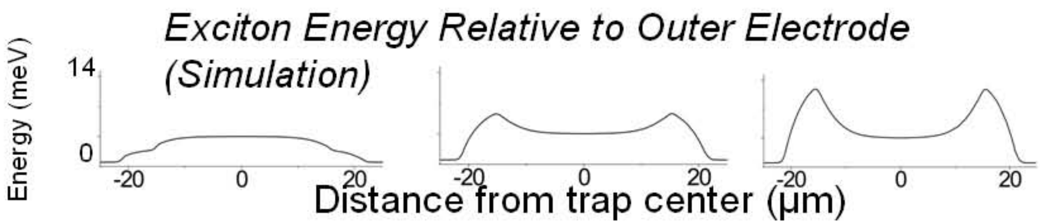
↓

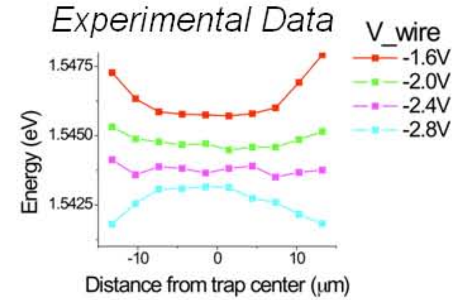
collect many excitons to the trap center

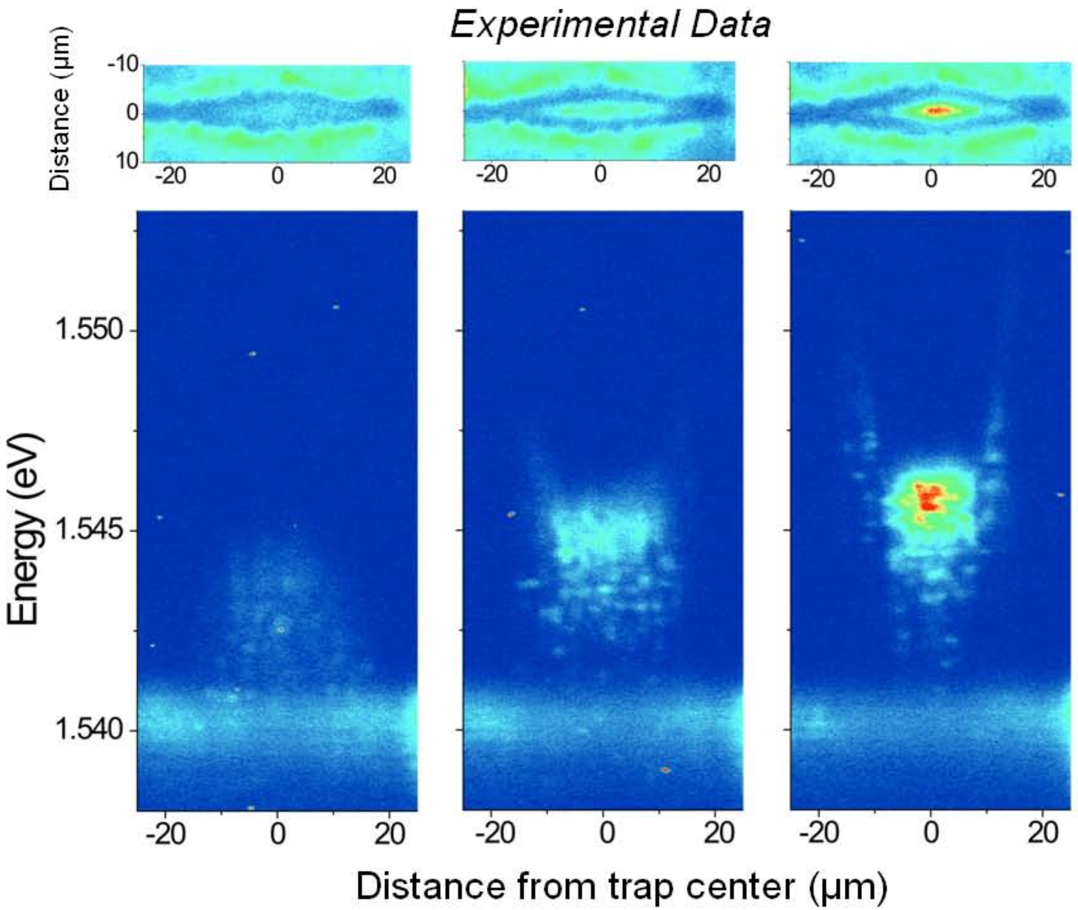


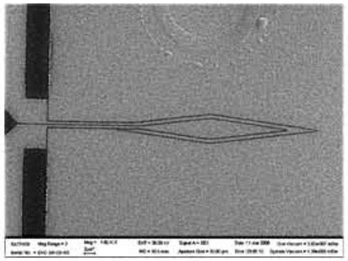
A.A. High, A.K. Thomas, G. Grosso, M. Remeika, A.T. Hammack, A.D. Meyertholen, M.M. Fogler, L.V. Butov, M. Hanson, A.C. Gossard, PRL 103, 087403 (2009)

Excitons in Elevated Diamond Trap









higher energy excitons escape the elevated trap at a higher rate

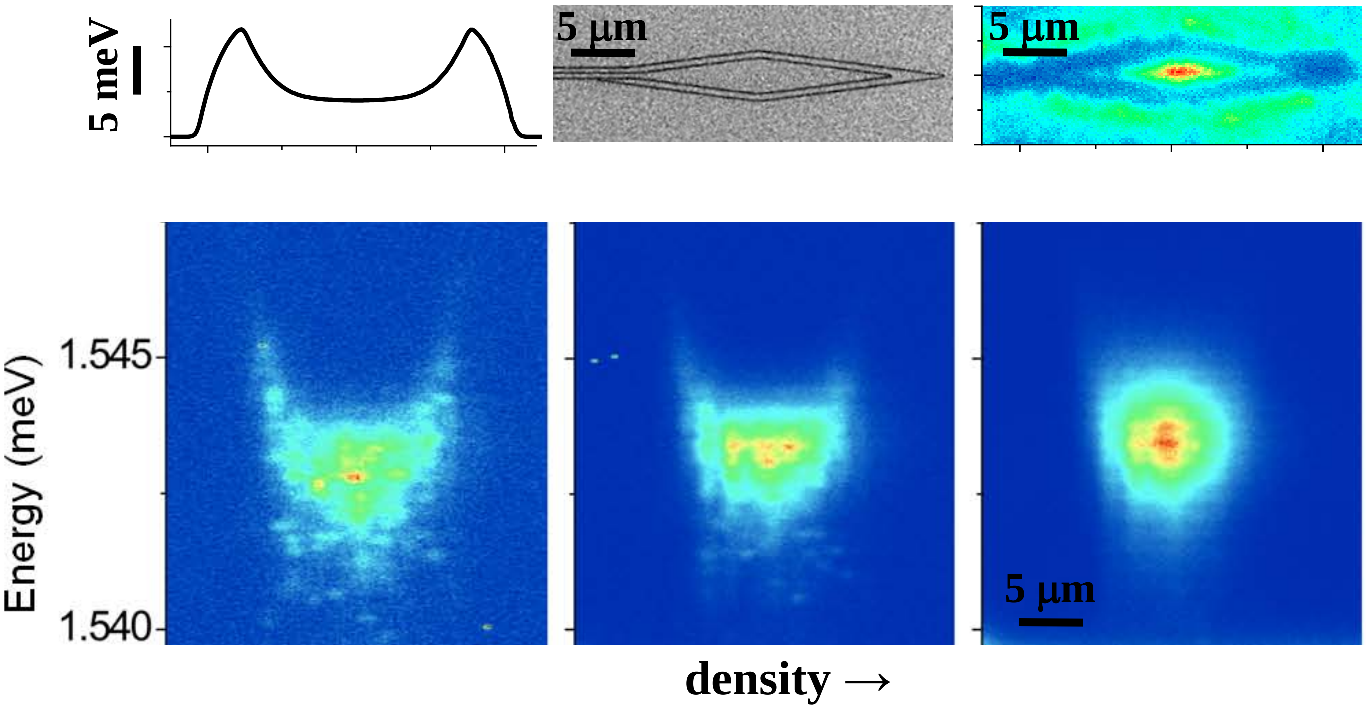
↓

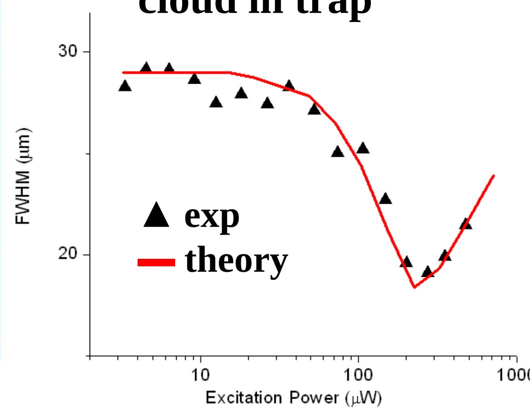
the excitons in the elevated trap undergo <u>evaporative cooling</u>

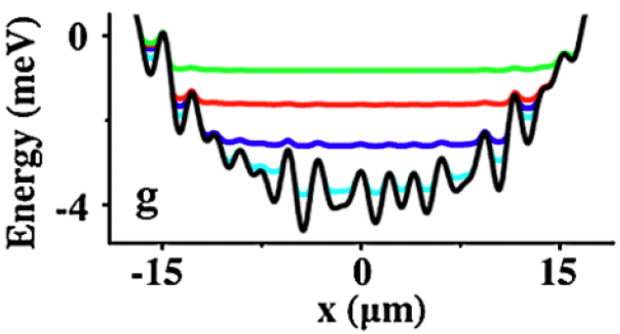
A.A. High, A.T. Hammack, L.V. Butov, L. Mouchliadis, A.L. Ivanov, M. Hanson, A.C. Gossard, Nano Lett. 9, 2094 (2009)

A.A. High, A.K. Thomas, G. Grosso, M. Remeika, A.T. Hammack, A.D. Meyertholen, M.M. Fogler, L.V. Butov, M. Hanson, A.C. Gossard, PRL 103, 087403 (2009)

Collection of exciton cloud to trap center with increasing density





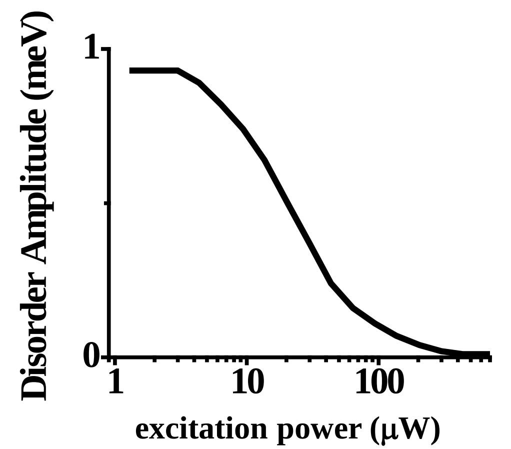


repulsive interaction

screening of disorder

collection to trap bottom

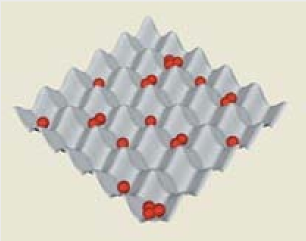
cold exciton gas in trap



can be controlled in situ like traps for cold atoms

Excitons in lattices

Atoms in lattices



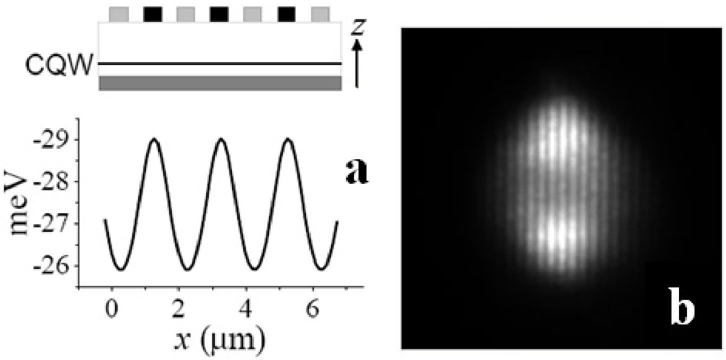
M. Greiner, O. Mandel, T. Esslinger, T.W. Hansch, I. Bloch, Nature 415, 39, (2002)
J.K. Chin, D.E. Miller, Y. Liu, C. Stan, W. Setiawan, C. Sanner, K. Xu, W. Ketterle, Nature 443, 961 (2006)

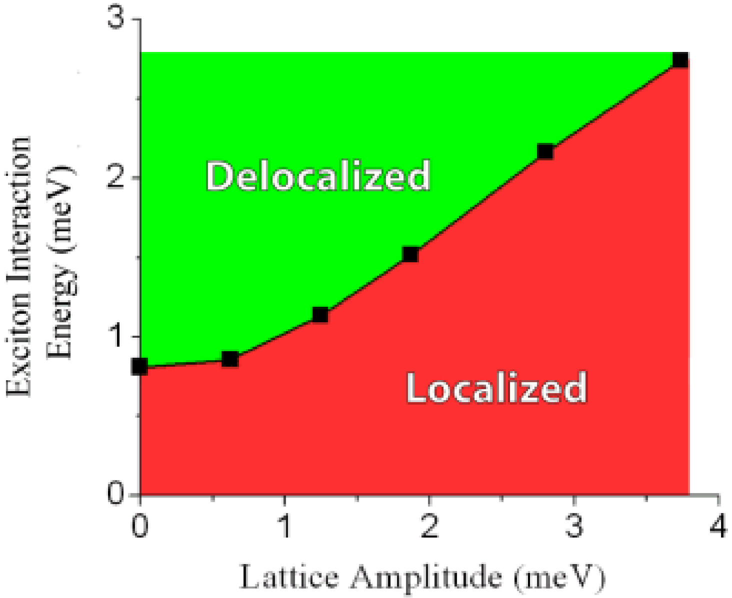
atoms in lattices – system with controllable parameters

⬇

use atoms in lattices to emulate solid state materials

Excitons in lattices





controllable: exciton density, interaction, mass
lattice amplitude, structure, constant

⬇

a tool with a number of control knobs
for studying the physics of excitons

M. Remeika, J. Graves, A.T. Hammack, A.D. Meyertholen, M.M. Fogler, L.V. Butov, M. Hanson, A.C. Gossard, PRL 102, 186803 (2009)

Transport of electrons, holes, excitons, and polaritons via SAW

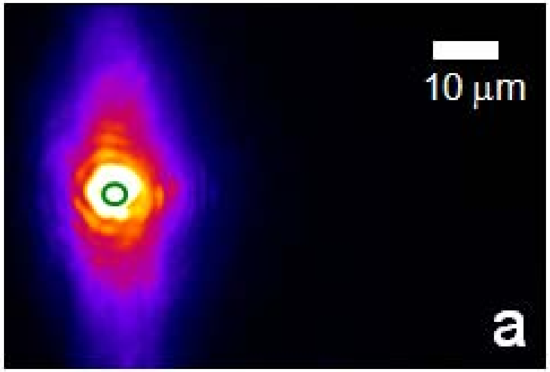
C. Rocke, S. Zimmermann, A. Wixforth, J.P. Kotthaus, G. Böhm, G. Weimann, PRL 78, 4099 (1997)
P.V. Santos, M. Ramsteiner, R. Hey, PSS B 215, 253 (1999)
J. Rudolph, R. Hey, P.V. Santos, PRL 99, 047602 (2007)

Electrostatic conveyers for excitons

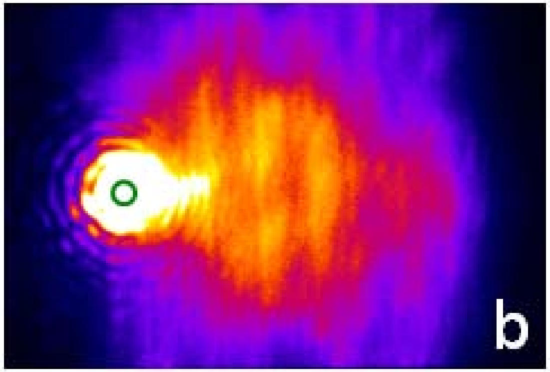
conveyers are created by applying AC voltages to lattice electrodes → traveling lattice

wavelength ← electrodes
amplitude ← voltage
speed ← frequency

conveyer off



conveyer on



study dynamic LDT
with varying
conveyer amplitude
conveyer speed
exciton density

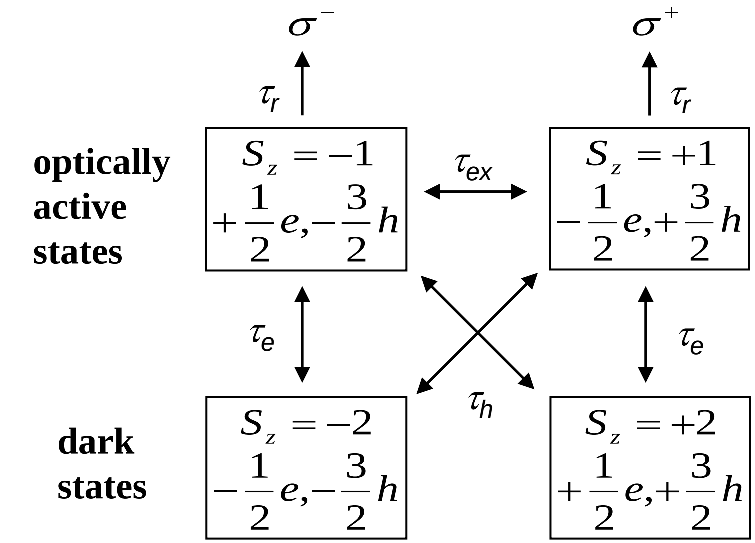
A.G. Winbow, J.R. Leonard, Y.Y. Kuznetsova, M. Remeika, A.A. High, E. Green, A.T. Hammack, L.V. Butov, J. Wilkes, A.L. Ivanov, M. Hanson, A.C. Gossard, unpublished

Spin transport of excitons

exciton spin transport over substantial distances requires

- **exciton transport over substantial distances**
- **long spin relaxation time**

Spin-Flip Pathways



M.Z. Maialle, E.A. de Andrada e Silva, L.J. Sham, PRB 47, 15776 (1993)

polarization relaxation time

$$\tau_P^{-1} = 2(\tau_e + \tau_h)^{-1} + \tau_{ex}^{-1}$$

$$P = \frac{I_+ - I_-}{I_+ + I_-}$$

τ_{ex} **is determined by exchange interaction between *e* and *h*** $\quad \tau_{ex} \propto \tau_r^2$

control τ_p by changing *e-h* overlap

GaAs SQW
direct exciton

$\tau_P \sim \tau_{ex}$

fast depolarization within tens of ps

GaAs CQW
indirect exciton
with small *e-h* overlap

$\tau_P \sim \tau_e / 2$

orders of magnitude enhancement of exciton spin relaxation time

⬇

makes possible exciton spin transport over substantial distances

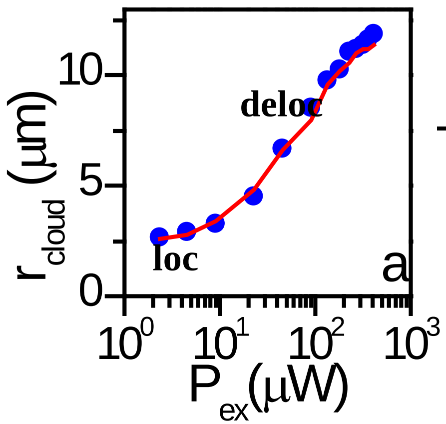
$\Delta_{bright-dark} \propto \tau_r^{-1}$

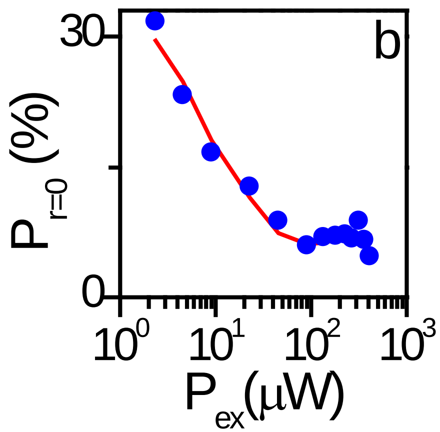
$\sim 0.1\,\text{meV}$ ← **GaAs SQW direct exciton**

$\sim 0.1\,\mu\text{eV}$ ← **GaAs CQW indirect exciton with small *e-h* overlap**

J.R. Leonard, Y.Y. Kuznetsova, Sen Yang, L.V. Butov, T. Ostatnick´y, A. Kavokin, A.C. Gossard, Nano Lett. 9, 4204 (2009)

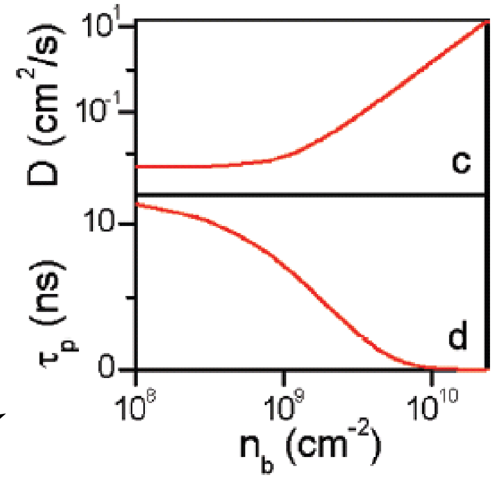
Density dependence

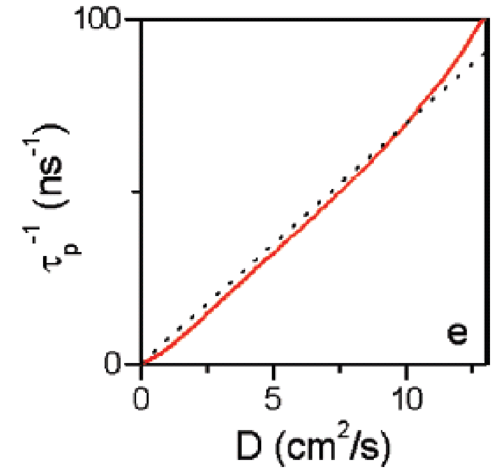




$$r_{cloud} \sim (D\tau_r)^{1/2}$$

$$P = \frac{\tau_p}{\tau_P + \tau_r}$$



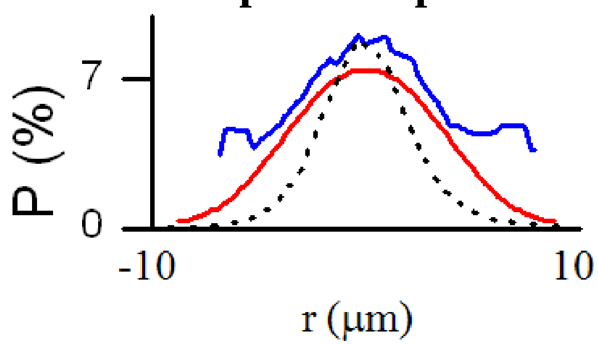


P **and τ_P drop with increasing density (or *T*)**

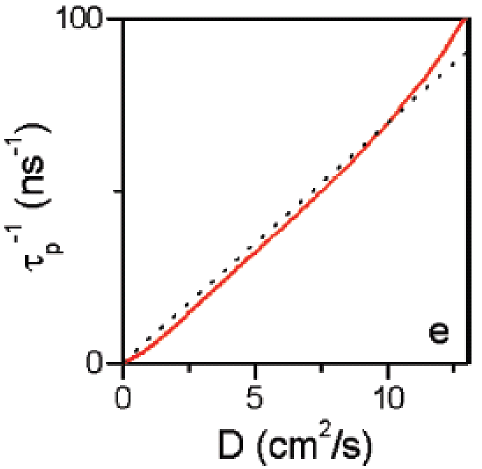
decrease of τ_P is correlated with the increase *D*
$\rightarrow$ τ_P drops when excitons become delocalized

complies with D'yakonov - Perel' spin relaxation mechanism

spin transport



Decrease of *P* and τ_P with increasing density



complies with D'yakonov-Perel' spin relaxation mechanism

spin relaxation time $\tau_e^{-1} = \left\langle \Omega_e^2 \tau \right\rangle$

$\Omega_e = 2\beta k/\hbar$ frequency of spin precession

$\tau \approx m_{ex} D / k_B T$ momentum scattering time

$k_T = \left(2 m_{ex} k_B T / \hbar^2\right)^{1/2} m_e / m_{ex}$

$$\tau_P^{-1} = 2\tau_e^{-1} = 16\beta^2 m_e^2 D / \hbar^4$$

spin splitting constant

experiment: $\beta \approx 25\,\mathrm{meV\dot{A}}$

theoretical estimate: $\beta \approx 20\,\mathrm{meV\dot{A}}$

Topological defects in interference pattern

Vortices

quantized vortex is characterized by point (or line) around which phase of wave function varies by $2\pi n$

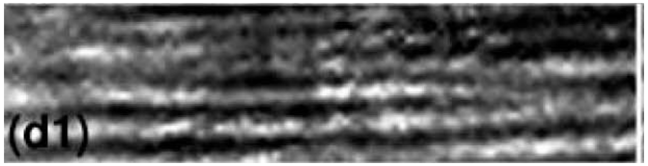
fork-like dislocation in phase pattern is signature of quantized vortex

quantized atom vortices

S. Inouye, S. Gupta, T. Rosenband, A.P. Chikkatur, A. Görlitz, T.L. Gustavson, A.E. Leanhardt, D.E. Pritchard, W. Ketterle, PRL 87, 080402 (2001)

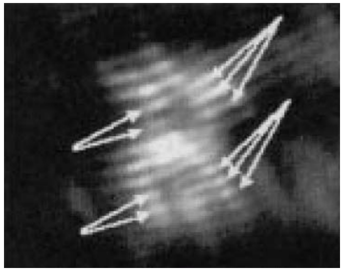
F. Chevy, K.W. Madison, V. Bretin, J. Dalibard, PRA 64, 031601(R) (2001)

Z. Hadzibabic, P. Krüger, M. Cheneau, B. Battelier, J. Dalibard, Nature 441, 1118 (2006)



quantized optical vortices

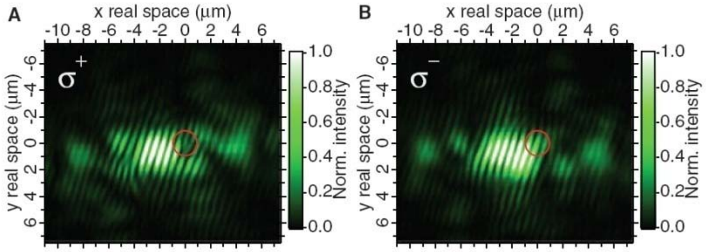
J. Scheuer, M. Orenstein, Science 285, 230 (1999)
and references therein



quantized polariton vortices

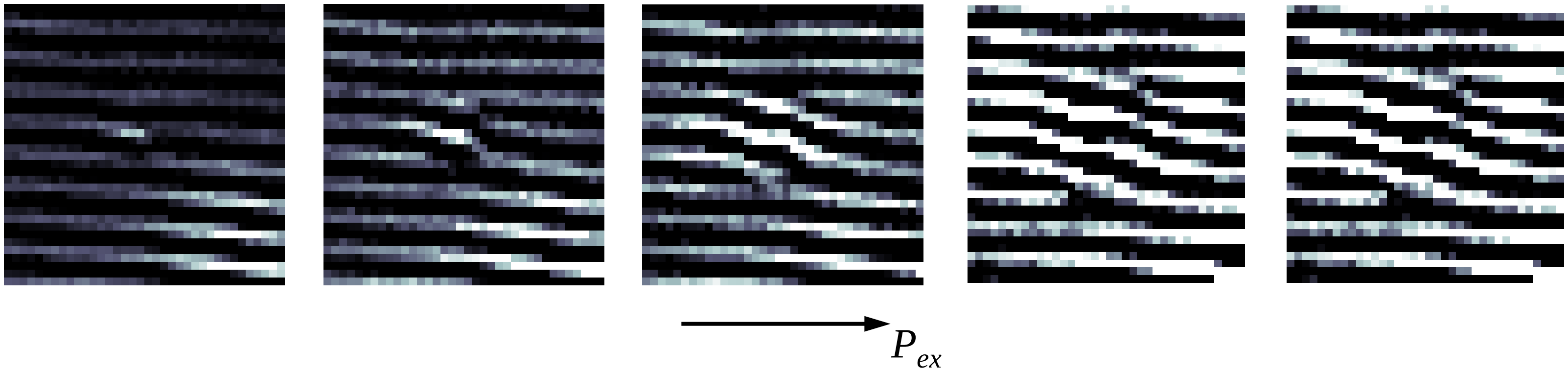
K.G. Lagoudakis, M. Wouters, M. Richard, A. Baas, I. Carusotto, R. André, Le Si Dang, B. Deveaud-Plédran, Nature Physics 4, 706 (2008)

K.G. Lagoudakis, T. Ostatnický, A.V. Kavokin, Y.G. Rubo, R. André, B. Deveaud-Plédran, Science 326, 974 (2009)

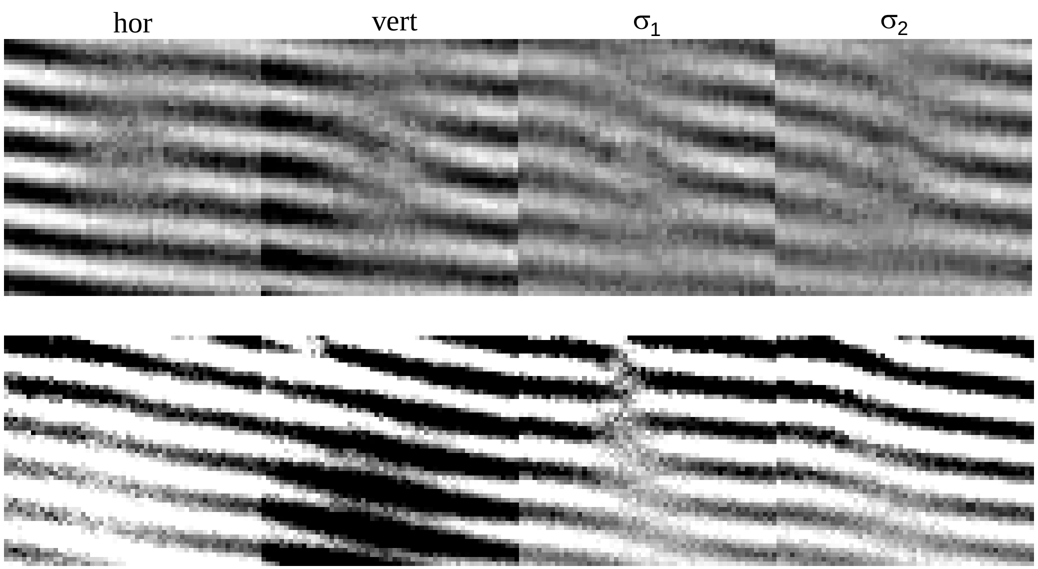


polariton half-vortices

Fork-like topological defects in interference pattern of indirect excitons



for different polarizations



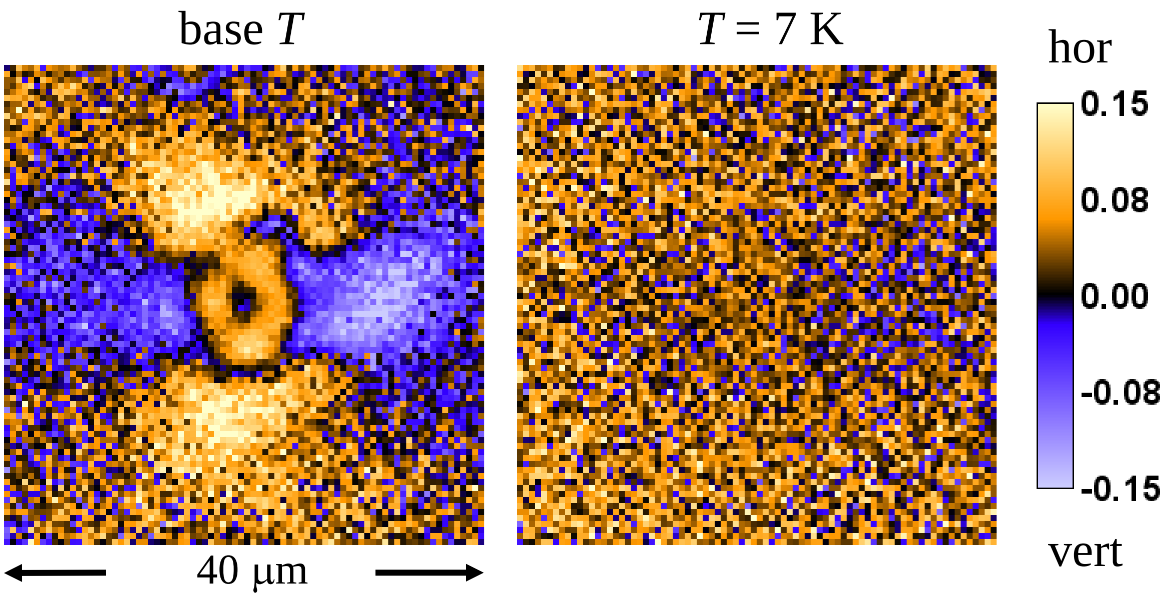
theoretical study of topological defects in multicomponent spin excitonic systems

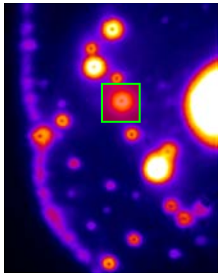
Y.G. Rubo, PRL 99, 106401 (2007)

A.A. High, A.T. Hammack, J.R. Leonard, L.V. Butov, T. Ostatnický, A. Kavokin, Y.G. Rubo, A.C. Gossard, unpublished

Spin pattern formation

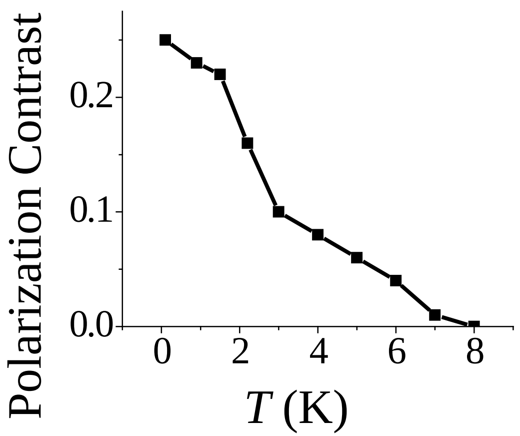
Linear polarization

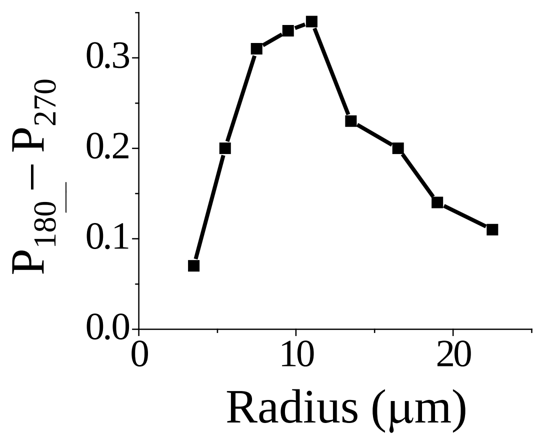




Data:

- **polarization rings**
- **polarization vortex: linear polarization is perpendicular to radial direction**

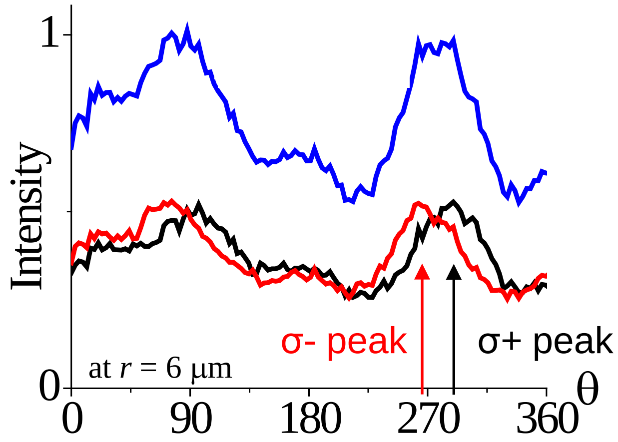




Pattern of linear polarization

- **forms spontaneously**
- **is observed up to large distances from the origin**
- **is observed at low *T***

Circular polarization

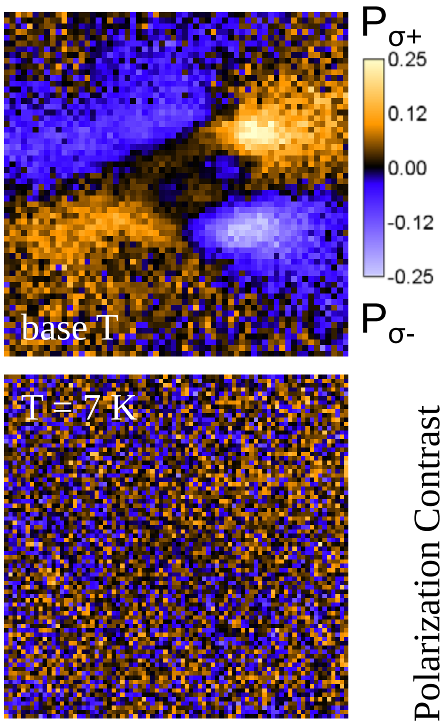


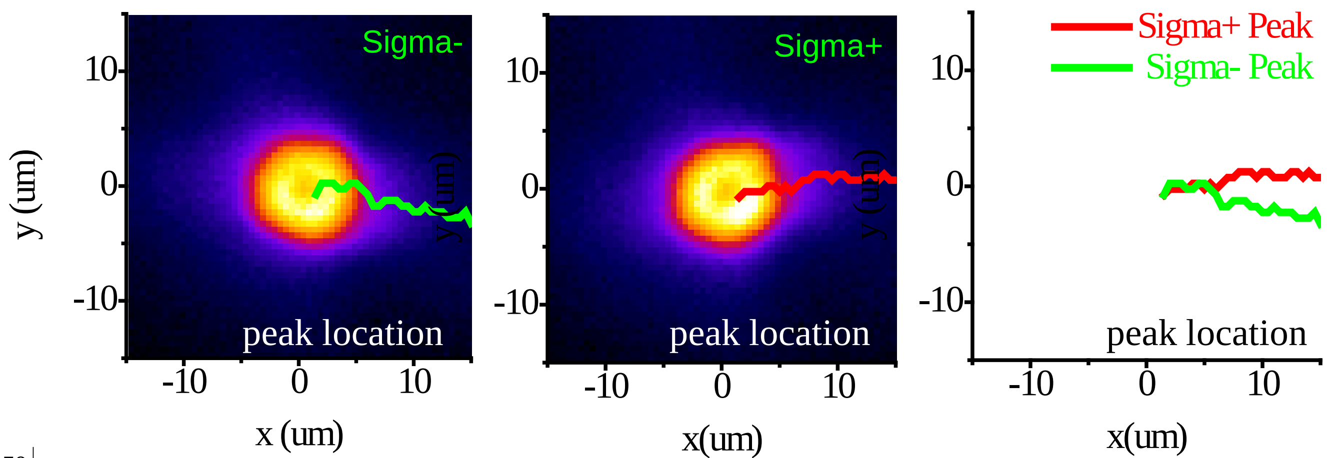
Data:

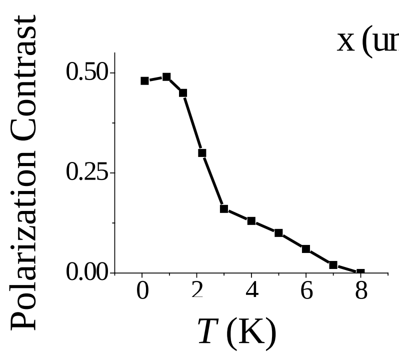
- **skew of circular polarized fluxes around 90^0 and 270^0**

Pattern of circular polarization

- **forms spontaneously**
- **is observed up to large distances from the origin**
- **is observed at low *T***







Experiments on cold excitons in CQW

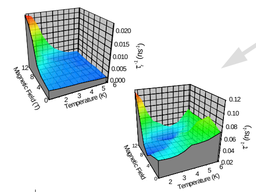
- **Realized cold exciton gases with $T \ll T_{dB}$**
- **Observed in cold exciton gases:**
  - **Evidence for phenomena expected for exciton BEC**

not discussed
in this presentation

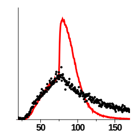
consistent with onset of

enhancement of exciton

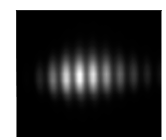
- radiative decay rate → superradiance
- mobility → superfluidity
- scattering rate with increasing density → stimulated scattering
- coherence length → spontaneous coherence



PRL 73, 304 (1994)
PRB 58, 1980 (1998)

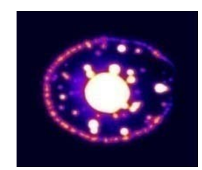


PRL 86, 5608 (2001)



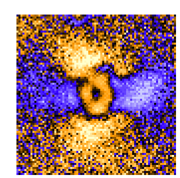
PRL 97, 187402 (2006)

  - **Macroscopically ordered exciton state**



Nature 418, 751 (2002)

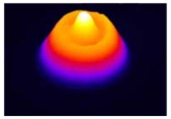
  - **Topological defects in interference pattern**
  - **Spin pattern formation**



http://physics.ucsd.edu/~lvbutov

Control of cold excitons

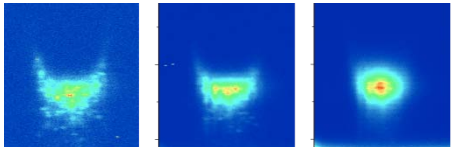
- **Excitons in laser induced traps**
  - Trapping of cold excitons in laser-induced traps
  - Hierarchy of times $\tau_{cool} << \tau_{load} << \tau_{rec}$ is favorable for control of cold excitons



PRL 96, 227402 (2006)

PRB 76, 193308 (2007)

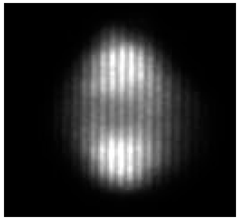
- **Excitons in electrostatic traps**
  - Exciton collection to trap center with increasing density, screening of disorder, realization of cold exciton gas at trap center
  - Evaporative cooling of excitons in elevated traps



Nano Lett. 9, 2094 (2009)

PRL 103, 087403 (2009)

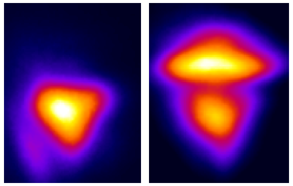
- **Excitons in lattices**
  - Localization-delocalization transition with reducing lattice amplitude or increasing exciton density
  - Estimating strength of disorder and exciton interaction



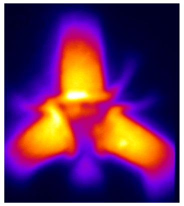
PRL 102, 186803 (2009)

Excitonic devices

- **Excitonic transistor**
  - Prototype performs switching at speeds > 1 GHz
  - Compact: 3 μm between source and drain
  - Scalable: have architecture and operation principle similar to FET
  - Operation of excitonic switches at ~ 100 K



- **Simple excitonic integrated circuits**
  - Prototype performs directional switching and merging



Opt. Lett. 32, 2466 (2007)

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Nature Photonics 3, 577 (2009)

Opt. Lett. 35, 1587 (2010)

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Yuri Rubo, *Cuernavaca*
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